D. KOZAK, I. SAMARDŽIĆ, P. KONJATIĆ

ISSN 0543-5846
METABK 48(2) 79-82 (2009)
UDC – UDK 669.14.018:620.172.24=111

FRACTURE MECHANICS PARAMETERS ESTIMATION OF CCT SPECIMENS MADE OF X 5 CrNi 18 10 STEEL

Received – Prispjelo: 2008-06-24
Accepted – Prihvaćeno: 2008-09-20
Original Scientific Paper – Izvorni znanstveni rad

This study investigates fracture behaviour of specimens made of high ductile stainless steel. Investigated material was X 5 CrNi 18 10 steel and the specimens used in this investigation were prepared as centre crack tension (CCT) specimens. Pre-cracking of specimens was done by controlled cycling loading. For determination of J-integral, as one of important fracture mechanics parameters, a single specimen method with loading-unloading procedure was used. The same experiment was numerically modelled by using commercial software for finite element analysis – ANSYS. The standard node releasing technique was implemented in finite element method simulation to simulate crack propagation. Numerically obtained results were compared to the results obtained by experiment.

Key words: ductile stainless steel, fracture mechanics parameters, CCT specimen, finite element method

Izračun i procjena parametara mehanike loma CCT uzoraka načinjenih od čelika X 5 CrNi 18 10. U ovome radu se proučava lomno ponašanje uzoraka načinjenih od visoko duktilnog nehrđajućeg čelika. Istraživani materijal je čelik X 5 CrNi 18 10, a uzorci koji su korišteni u ovoj studiji su pripremljeni kao standardni CCT uzorci. Kontroliranim cikličkim opterećenjem na uzorcima je napravljen inicijalni rast pukotine. Za određivanje J-integrala kao jednog od važnih parametara mehanike loma korištena je metoda jednog uzorka s postupkom opterećivanja i rasterećivanja. Isti eksperiment je i numerički modeliran koristeći komercijalni softverski paket za metodu konačnih elemenata – ANSYS. U simulaciji metodom konačnih elemenata implementirana je standardna tehnika otpuštanja čvorova kako bi bio simuliran rast pukotine. Numerički dobiveni rezultati su uspoređeni s rezultatima koji su dobiveni eksperimentom.

Ključne riječi: duktilni nehrđajući čelik, parametri mehanike loma, CCT uzorak, metoda konačnih elemenata

INTRODUCTION

For a reliable operation of structures and their components during exploitation period, it is crucial to monitor continuously or periodically check the integrity of structure. In the production and during exploitation, a certain amount of flaws can be encountered in any structure. It is important to determine how such flaws can influence the safety and reliability of the operation. Since fracture mechanics deals with fracture and fracture behaviour of materials, it gives a methodology which can be used to evaluate structural integrity of components containing such flaws considering cracks in the first place. In assessing the integrity of structures containing cracks, it is important to quantify the relevant crack-driving force, so that the load carrying capacity can be predicted. If it is the case with components made of ductile materials, which generally exhibit slow and stable crack growth and which are able to provide large-scale plasticity near the crack tip, this crack-driving force is frequently described as contour *J*-integral [1]. It stands for a suitable elastic-plastic fracture mechanics parameter, for materials that possess low strength and high material toughness, but not sufficient enough to fully describe fracture behaviour of such materials [2] especially if crack growth is present, because the basis of *J*-integral concept considers stationary crack [1] and its value may become inaccurate because of path dependence for the growing crack. Therefore, beside *J*-integral, the data of crack growth must be obtained to allow construction of crack resistance curve and if certain size and geometrical conditions are fulfilled [3] then constructed crack resistance curve can be considered as one of the material properties. All fracture parameters are generally divided into two groups, one considering local parameters describing the near crack tip fields, like crack tip opening displacement *CTOD*, and other considering global parameters that usually represent some type of energy, such as *J*-integral. Since local crack tip generally controls the crack growth, local fracture parameters are more accurate in predicting fracture behaviour than global ones and they are expected to be independent of specimen size and geometry and loading configuration [4]. Therefore, in this paper, which describes fracture

D. Kozak, I. Samardžić, P. Konjatić; Faculty of Mechanical Engineering, University of Osijek, Slavonski Brod, Croatia

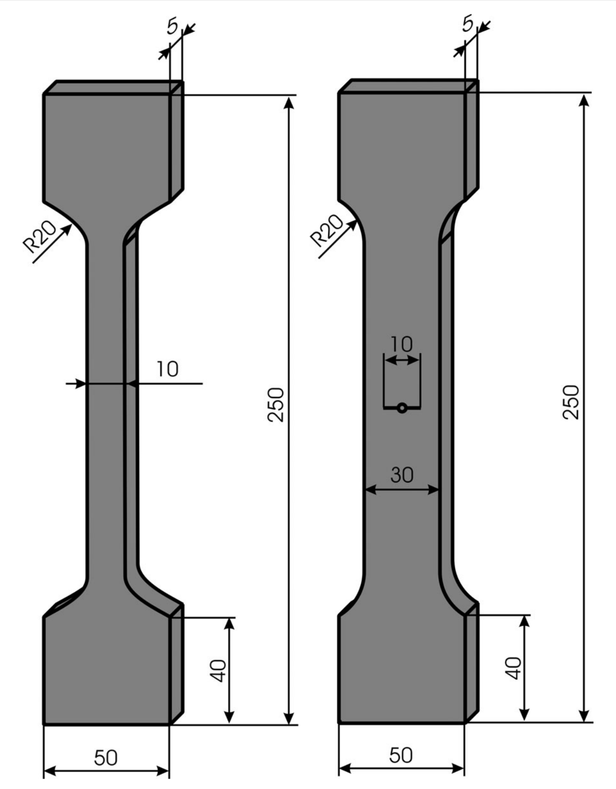
behaviour of one stainless steel that possesses high ductility, previously mentioned fracture mechanics parameters were obtained from specimens prepared for testing and also numerically by using finite element method. Crack resistance curve was evaluated to establish its compliance with the required conditions to fully describe the tested material property.

EXPERIMENTAL WORK

The material used in this investigation was high ductile stainless steel X 5 CrNi 18 10, with yielding strength of $R_{p0,2}$ = 250 MPa and tensile strength of 620 MPa by elongation of about 16 %. Firstly, series of tests were conducted on specimens prepared for classic tension test, shown in Figure 1.a), to determine real characteristics of material including $\sigma - \varepsilon$ diagram, and later on standard centre crack tension (CCT) specimens for determination of fracture mechanics parameters shown in Figure 1.b), with ratio of crack length and specimen width of $2a/W$ = 10/30 = 0,3 [5].

In order to obtain the required fracture mechanics parameters, CCT specimens were pre-cracked in such a manner that under controlled cycling loading the crack extension has increased to 2,5 mm on both sides of the notch (Figure 2) in the middle of the specimen and then a single specimen method with loading-unloading procedure was used.

In characteristic stages of test CTOD in terms of δ_5 [6], as local fracture parameter, is measured by using



a) tension test specimen b) CCT specimen

Figure 1. Tension test and CCT specimen

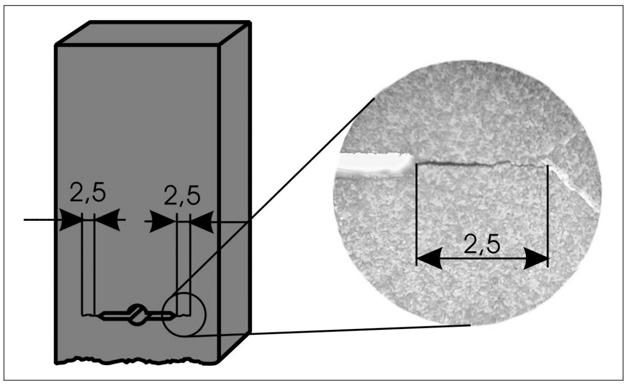


Figure 2. Pre-cracking of CCT specimens

gages located on the exact place of crack tip at distance of 5 mm (2,5 mm above and 2,5 mm below the crack tip). J-integral as global parameter and crack growth values were obtained by using measured compliance according to ASTM E 1152 [7] to construct resistance curve based on the J-integral (J-R resistance curve). The value of J-integral can also be directly measured on the fracture toughness specimen itself, if array of strain gages are attached in a contour around the crack tip [8], but it requires highly cumbersome instrumentation and therefore is not used in this case.

CRACK RESISTANCE CURVE

A considerable number of papers dealing with J-integral based resistance curve (J-R curve) was published including [9], [10] and [11]. Since J can be applied only for linear and nonlinear elasticity (deformation plasticity), the crack resistance curve varies with specimen size, geometry and the value of crack extension for crack growth in elastic-plastic materials [10, 12] and therefore cannot be considered as a material characteristic curve [4]. Some analyses proved that under specific conditions J-controlled crack growth can exist [12] and that different specimen geometry has the same far field J-integral resistance curves only under plane stress conditions [13]. According to [3] a valid J-R curve in the plane stress case can only be obtained up to about:

$$\Delta a^* = (0{,}2 - 0{,}3) \cdot b_0 \qquad (1)$$

meaning that crack growth at R-curve splitting has to be less than 30 % of the initial size of the remaining ligament length of specimen. In this investigation this condition is fulfilled, because crack extension after crack initiation was about 4 mm [5] and previously investigation also verified the validity of obtained J-R curve [14] and it can be concluded that resistance curve can be considered as material property and therefore a subject for further investigation.

FINITE ELEMENT ANALYSIS

Finite element analysis was performed in ANSYS code [15] on a prepared three-dimensional model of speci-

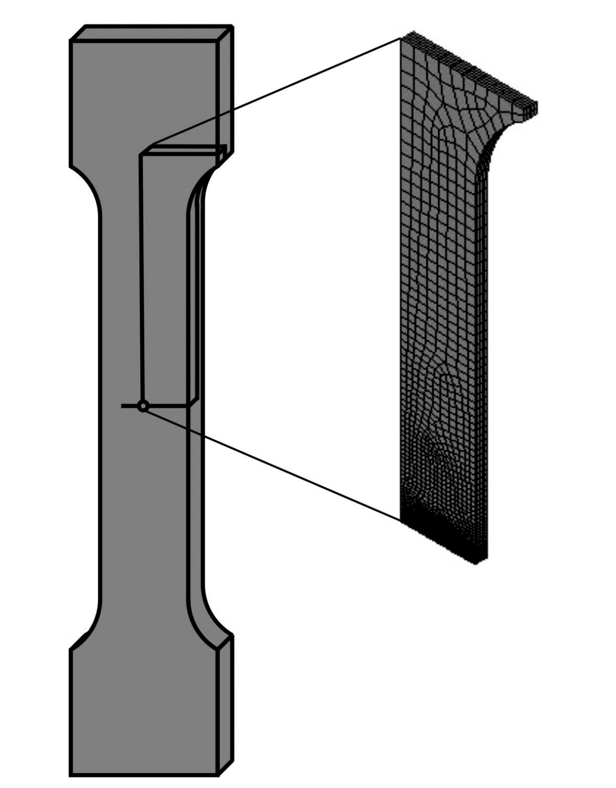


Figure 3. Finite element model of 1/8 of CCT specimen

men, modelled as 1/8 of real CCT specimen taking the symmetry into account (Figure 3).

Finite element mesh consisted of 16780 three-dimensional 20-node isoparametric elements and 79392 nodes. The regions of less interest are meshed with coarse mesh. The region surrounding crack tip and the region along the crack propagation path were finely meshed. The specimen was loaded quasi-statically in order to simulate a loading-unloading procedure performed in the experiment. To simulate crack propagation, a standard node releasing technique was used. At the end of every full loading cycle, just after the process of unloading, a crack extension has been added to the initial crack length simulating crack growth by freeing the nodes along the predefined crack extension path. For every crack extension, the value of J was calculated and those results of finite element analysis are presented in form of diagrams.

RESULTS AND CONCLUSIONS

Crack resistance curve obtained by the experiment and numerical analysis is presented in Figure 4. It can be seen that numerically obtained results closely follow the calculated J values. Figure 5 shows how applied force changes with load line displacement.

Due to better visibility, numerically obtained results of just some cycles of loading are displayed and compared to experimental results. Numerically derived *F-LLD* curve is slightly below the experimental one for force below 34 kN and slightly above for higher values

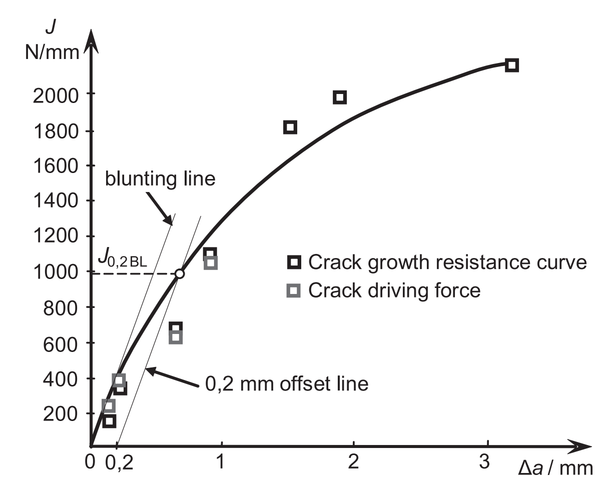


Figure 4. *J–R* resistance curve

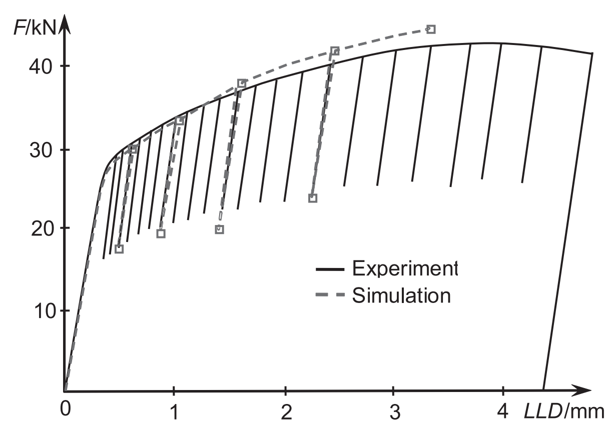


Figure 5. Experimentally and numerically obtained *F-LLD* curves

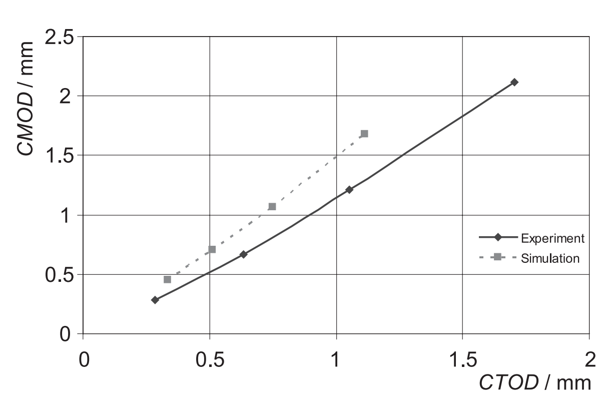


Figure 6. Experimentally and numerically obtained *CMOD* - *CTOD* curves

of the applied force, but anyway it also shows a good match between the experiment and the simulation. How crack mouth opening displacement changes in relation to crack tip opening displacement in terms of δ_5 is shown in Figure 6.

Four stages of test are presented on each curve as dots and they correspond to the same stage of test (either experimental or numerical). At the first two stages the simulation shows higher values of *CMOD* but later it shows lower values than values obtained by experiment. That indicates that simulation in the first stages is more on the conservative side, but afterwards it tends to overvalue material properties considering *CMOD* values. When *CTOD* is taken into account, only the first stage of simulation gives closer and lower values than the experiment. That can lead to a conclusion that finite element analysis for similar problems (considering material, size and geometry), even when showing close match in some parameters (Figure 4 and Figure 5), has to be very carefully used considering CMOD and CTOD values.

Acknowledgment: The authors wish to thank to the Croatian Ministry of Science, Education and Sports for supporting this investigation through projects: Analysis and fracture assessment of structures of anisotropic materials (No. 152-1201910-1909) and Advanced joining technology in light mechanical constructions (No. 152-1521473-1476).

REFERENCES

[1] J.R. Rice, A path independent integral and the approximate analysis of strain concentrations by notches and cracks, Journal of applied mechanics, 35 (1968), 379-386.

[2] T.L. Anderson, Fracture Mechanics: Fundamentals and Applications, CRC Press, 1995

[3] K.H. Schwalbe, Ductile crack growth under plane stress conditions: Size effects and structural assessment – I. Size and geometry effects on crack growth resistance, Engineering Fracture Mechanics, 42 (1992) 2, 211-219.

[4] T.L. Weng, C.T. Sun, A study of fracture criteria for ductile materials, Engineering Failure Analysis, 7(2000), 101-125.

[5] F. Matejiček, D. Kozak, P. Konjatić, Fracture behaviour of high ductile CCT specimen under elastic-plastic conditions, Extended Abstracts and Proceedings (CD-Rom Edition) of the 4th International Congress of Croatian Society of Mechanics – ICCSM 4, F. Matejiček (Ured.), Bizovac (2003) str. 601-608.

[6] D. Hellmann, K.-H. Schwalbe, Geometry and size effects on J-R and d-R curves under plane stress conditions, ASTM STP 833, (1984), 577-605.

[7] ASTM E 1152-87, Standard test method for determining J-R curves, American Society for Testing and Materials, Philadelphia, 1987.

[8] D. T. Read, Applied J-Integral in HY130 Tensile Panels and Implications for Fitness for Service Assessment, Report NBSIR 82 – 1670, National Bureau of Standards, Boulder, Colorado, 1982.

[9] P. Albrecht, W.R. Andrews, J.P. Gudas, J.A. Joyce, F.J. Loss, D.E. McCabe, D.W. Scmidt, W.A.Van Der Sluys, Tentative tests procedure for determining the plane-strain J-R curve, Journal of Testing and Evaluation, (1982), 245.

[10] J.D. Landes, D.E. McCabe, H.A. Ernst, Geometry effects on the R-curve, Nonlinear fracture mechanics: Vol. II – Elastic-Plastic Fracture, ASTM STP 995, (1989), 123.

[11] O. Kolednik, On the physical meaning of the J-Δa – curves, Engineering Fracture mechanics, (1991) 38, 403.

[12] I.W. Hutchinson, P.C. Paris, Stability analysis of J-controled crack growth, Elastic-Plastic Fracture, ASTM STP 668, (1979), 37.

[13] J. Sun, Z. Deng and M. Tu, Plane stress elastic-plastic fracture criteria and constraint intensity in crack-tip region, Engineering Fracture Mechanics 36 (1990), 321-326.

[14] F. Matejiček, D. Kozak, P. Konjatić, Validity of J-R resistance curve in the case of ductile crack growth, Extended Abstracts of the 21st Danubia-Adria Symposium on Experimental Methods in Solid Mechanics, Croatian Society of Mechanics, S. Jecić, D. Semenski (Ured.) (2004), str. 216-217.

[15] ANSYS 6.0, 2002.

Note: The language lecturer for English language is prof. Željka Rosandić, Faculty of Mechanical Engineering, Slavonski Brod.